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## Superconducting Fault Current Limiter Project

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*HTS Solutions for a New Dimension in Power*

Superconductivity for Electric Systems – 2006 Annual DOE Peer Review

## **HTS Fault Current Limiters New Technology for a Growing Problem**

**As new sources of generation are added, utilities are faced with the threat of higher levels of fault current**

- HTS Fault Current Limiters (FCLs) address the market pull to cost-effectively correct fault current over-duty problems at the transmission voltage level of 138kV and higher
- The HTS FCLs will reduce the available fault current to a lower, safer level so existing switchgear can still protect the grid

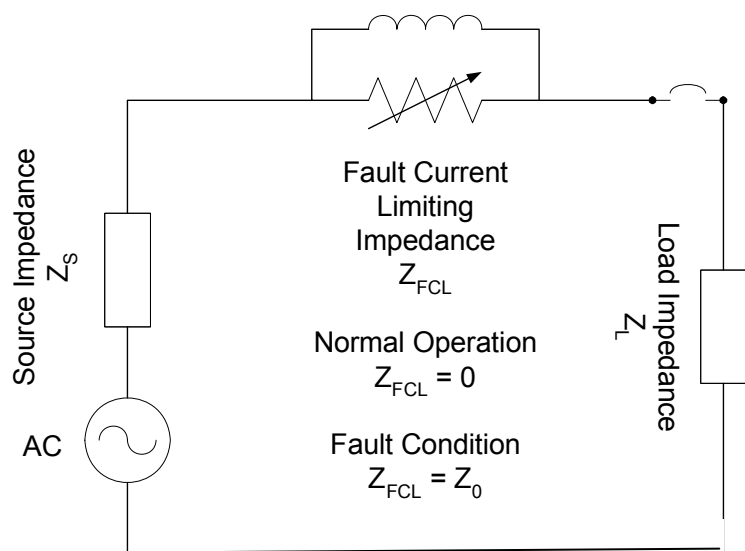
### **Utility market needs at the transmission level:**

- Accommodate increasing fault currents due to added generation
- Avoid adverse side effects imposed by existing solutions
- Prevent breaker failures and & problems (e.g., welded contacts, bus bracing, etc.)
- Reduce “through fault” stresses on aging infrastructure
- Maintain flexibility to accommodate load growth and “open access”
- Avoid need for expensive 80kA breakers

**HTS FCLs will be needed for most commercial AC HTS cable systems**

**Discussions with 20+ utilities have consistently validated the need!**

# Superconducting Fault Current Limiter (SFCL): An Alternative



Under fault conditions critical current is exceeded and the superconductor transitions to a resistive state, introducing current limiting impedance into the grid with a parallel inductor

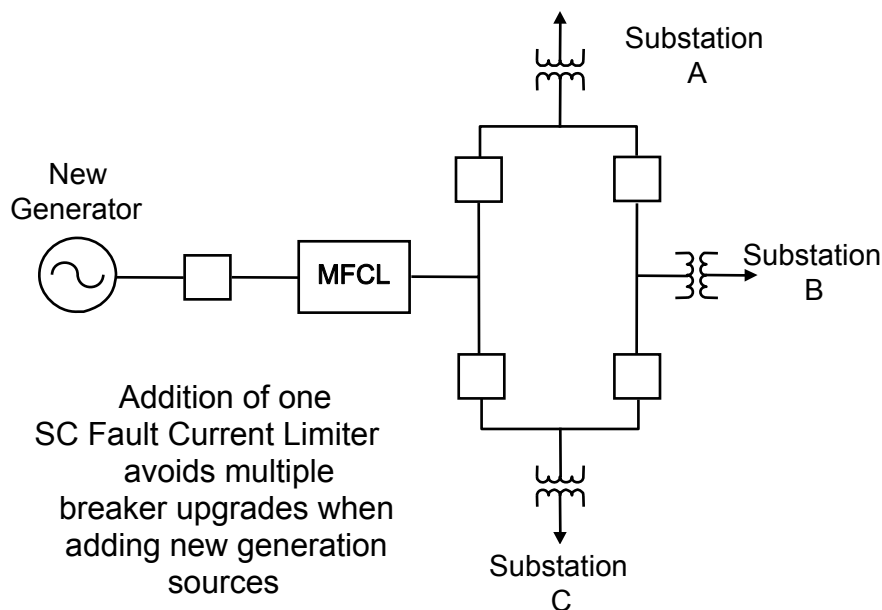
**New concept with no conventional counterpart:**

**Passive (no active controls for insertion in system),**

**No Burden on system during normal operation**

**Modular and Scalable**

**Environmental benefit and no SF6**



## Project Description & Research Integration

**Goal: Demonstrate SFCL feasibility at transmission level voltage – 138kV**

**Cost – Original \$12.2M project cost estimate, with \$6.1M DOE and \$600K EPRI support**

**Now estimating project cost \$23.6M, based on switch from melt cast BSCCO to 2G (\$2.4M) and one year program extension (total of two years – one for RES and one to optimize 2G for application)**

**Schedule – Project started 6/02, original completion 6/06 – Completion now estimated to be 6/09**

### **Project Team:**

- SuperPower, Inc.: Program Lead, supply of 2G matrix material
- Sumitomo Electric Industries, Ltd. (SEI) – High voltage bushings and cryostat electrical insulation system
- The BOC Group, inc. – Cryogenic refrigeration system
- American Electric Power (AEP) – Utility host, system studies
- DOE National Labs – CRADA executed with ORNL (High voltage, cryogenics), CRADA pending with LANL (HTS element evaluation)

## Research Integration (cont'd.)

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### Technical Advisory Board (TAB):

- Evaluate and guide project in conjunction with DOE Readiness Review
- Utility members: AEP, New York Power Authority, Southern California Edison, Con Edison, Entergy
- Academia: Rensselaer Polytechnic Institute (RPI)
- Funding sponsors: DOE and EPRI

### National Electrical Energy Testing, Research And Applications Center (NEETRAC)

- Periodic reviews with 5 utilities with an interest in the project: Florida Power and Light, Exelon, Southern Company, Baltimore Gas and Electric, Entergy
- Conference calls in March, June and July 2006
- NEETRAC project manager sits on TAB

### Use existing specialized facilities:

- KEMA Power Test, Chalfont, PA, for short circuit testing – 2G module tested in June 2006
- Waukesha Electric for Impulse testing up to 900kV – not this year during RES

### High Voltage Working Group – SEI, RPI, AEP and ORNL

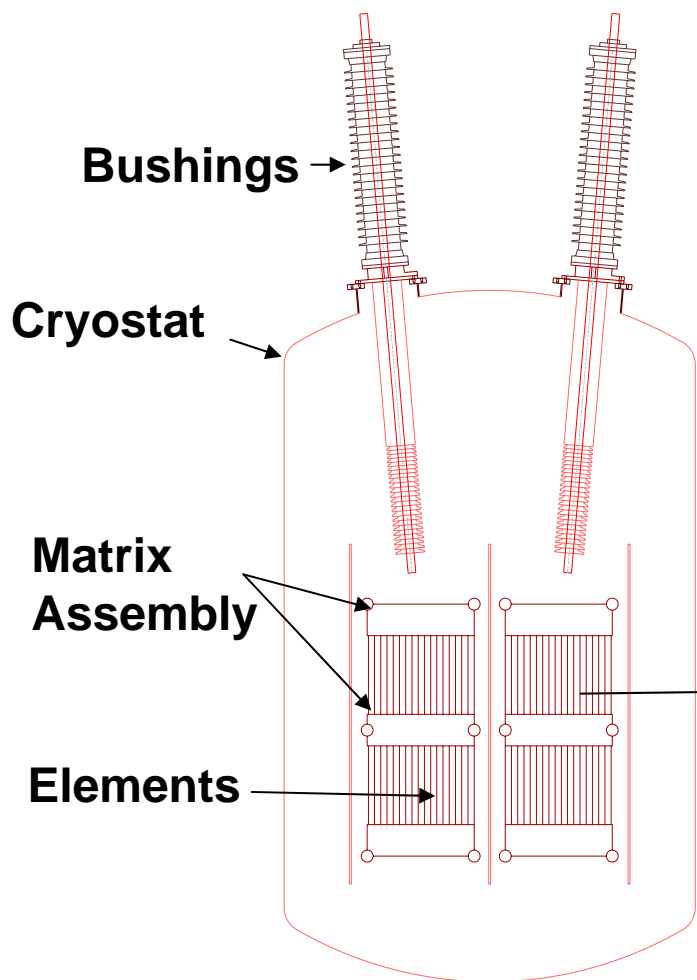
### Total of 5 US patents granted on SFCL technology

## Milestone Driven Program

Major Milestone	Objectives	Completion Date
<b>Concept Feasibility &amp; Application Studies</b>	<ul style="list-style-type: none"> <li>Complete Conceptual Design</li> <li>Study application requirements and perform power system studies</li> </ul>	Completed June 2003
<b>Proof-of-Concept Demonstration</b>	<ul style="list-style-type: none"> <li>Scaled hardware non-grid demonstration of matrix concept</li> </ul>	Completed July 2004
<b>Alpha Prototype</b>	<ul style="list-style-type: none"> <li>Focus: Scale up for non-grid demonstration at high voltage</li> <li>Rating: 138kV, single phase, AEP application requirements</li> </ul>	<b>ON HOLD</b>
<b>Beta Prototype</b>	<ul style="list-style-type: none"> <li>Focus: In-grid demonstration for specific utility application</li> <li>Rating: 138kV, three phase, AEP Sporn Application</li> </ul>	<b>ON HOLD</b>

**Fabrication of full scale prototypes on hold in July 2005 pending further developments in focus areas:**  
**1. High Voltage & 2. HTS elements**

# Alpha Prototype Development - Main Components

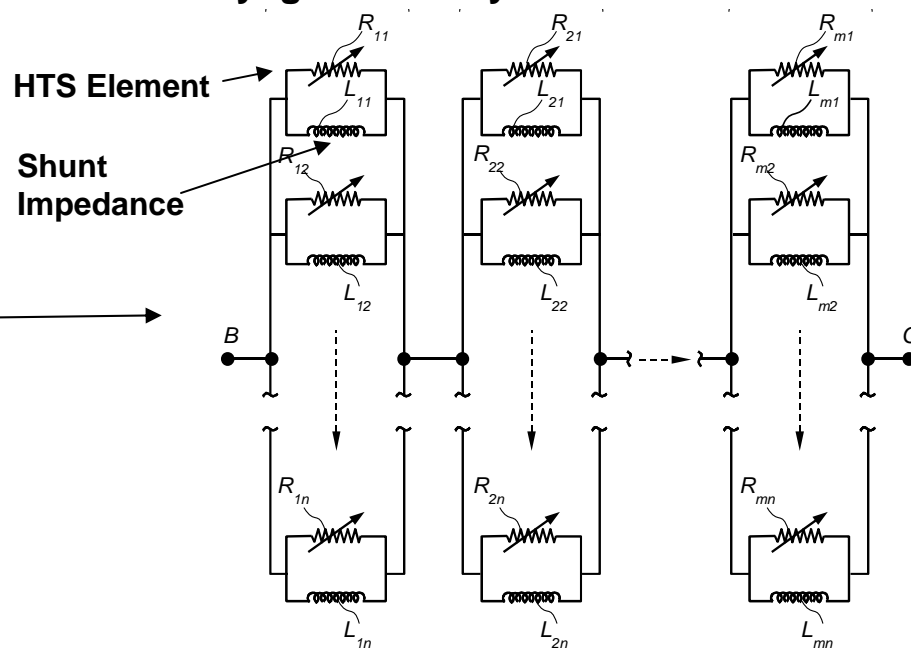


Single Phase of Alpha

High Voltage Insulation System – 1. Bushings, 2. Cryostat insulation system, 3. Matrix internal insulation

Matrix Assembly – 1. HTS Elements, 2. Connections of HTS elements and current limiting coils

Cryostat System – 1. Vessels to provide stable pressurized sub-cooled environment, 2. Cryogenics and cryocoolers



Simplified Matrix Assembly Schematic

## Program Status

- **At last year's Peer Review it was announced that the SFCL Program was being placed on hold (Alpha prototype design) due to:**
  - Concerns about the reliability of the melt cast BSCCO-2212 elements\*
  - Need for a partner with high voltage expertise\*
  - Escalating program cost

\* Both areas were identified at the 6/28/05 DOE Readiness Review as needing more priority
- **Shortly thereafter (September) stakeholders were informed that the program would be placed on Reduced Effort Status (RES) while SuperPower**
  - Investigated the feasibility of utilizing 2G material in the SFCL application
  - Obtained an industrial partner with high voltage expertise who is willing to share in the financial risk of the program
  - RES to last no later than 6/30/06
    - Reengage the program at full speed, or
    - Terminate the program

## Program Status (cont'd.)

- **In the last year during the RES**
  - The BOC Group, Inc. joined the project with responsibility for the cryogenic system design, development and device monitoring
  - Sumitomo Electric Industries, Ltd. (SEI) joined the project as the high voltage partner with responsibility for the bushings and cryostat electrical insulation system
  - Reconfirmed AEP participation as the beta prototype host site although the previously selected Sporn substation may change
  - Reaffirmed interest of TAB and NEETRAC utility members in the SFCL
  - Retained DOE and EPRI financial support albeit at a reduced levels
  - Obtained additional DOE support via the GridWorks program to specifically address optimization of 2G for the SFCL application
  - Demonstrated through in house and KEMA Power Lab testing that 2G is feasible for the SFCL application
- **Conclusions**
  - All conditions established to reengage the program at full pace have been fulfilled
  - The use of the same industrial partner team as the Albany Cable Project will build upon the close working relationships already established by world class organizations

## Melt Cast BSCCO Element Performance

- Testing of the BSCCO tube elements @ KEMA prior to last year's Peer Review
  - High probability of failure



- Low N value - typically  $I > 10 I_c$
- Limited cooling surface area - long recovery time typically of the order of 10s of Seconds
- Melt cast BSCCO tube length = 20 cm

## 2G SFCL Elements

### High Current and High Voltage Test @ KEMA

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#### Objectives

- ➔ Demonstrate the suitability of 2G tapes for current limiting at currents and voltages comparable to utility requirements provided for alpha and beta prototype SFCLs
  
- ➔ Verify in-house test results at higher currents and voltages
  - ◆ Dynamic resistance of the 2G tape
  - ◆ Failure mechanisms and performance limits – maximum current, voltage, energy, volts/cm and temperature rise
  - ◆ Life expectancy of the tape
  
- ➔ To carry out limited design studies of SFCL modules - Shunt coil design, spacing between 2G elements

# 2G SFCL 12 Element Module Assembly & KEMA Test

## 2G SFCL – Mockup assembly components

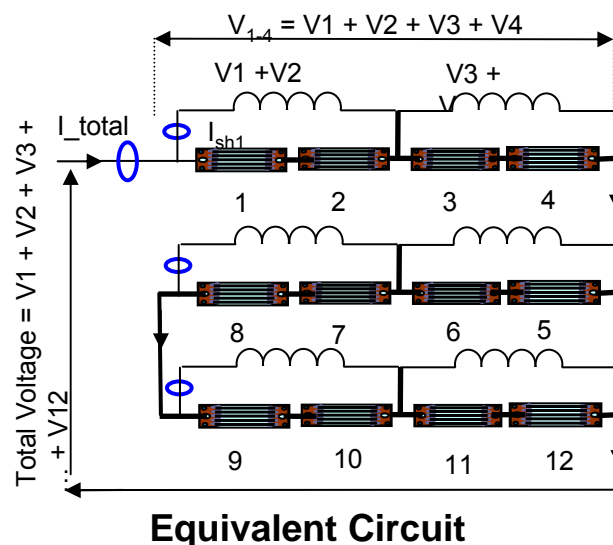
- ➔ 12 elements, 40 cm long with 4 2G tapes in parallel per element
- ➔ 12 elements connected in series
- ➔ 2 sets of 6 shunt coils of 10 mΩ and 5 mΩ

## Test Voltage and Current Ranges

- Voltage range from 120 V<sub>rms</sub> to 1200 V<sub>rms</sub>
- Fault current ranges from 3 kA peak to 100 kA peak

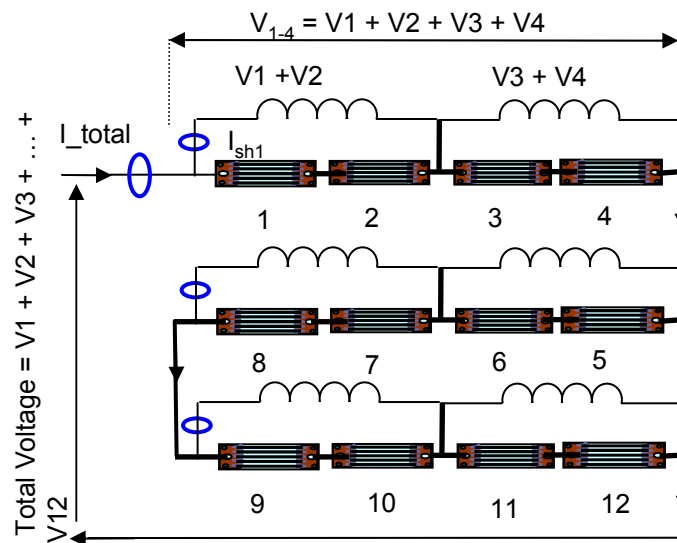
## Device Short Circuit Tests

- Start with the lowest fault current setup ( 5kA<sub>rms</sub> at 480 V<sub>rms</sub>) and lowest supply voltage setting, 120 V<sub>rms</sub>, and gradually step the voltage up to a maximum of 1200 V<sub>rms</sub>
- Repeat the above procedure with the 10 kA<sub>rms</sub> and 15 kA<sub>rms</sub> prospective fault currents
- Record voltage and current waveforms



## 2G Material Element Test Summary

- Testing of non optimized 2G material elements @ SuperPower & KEMA this year

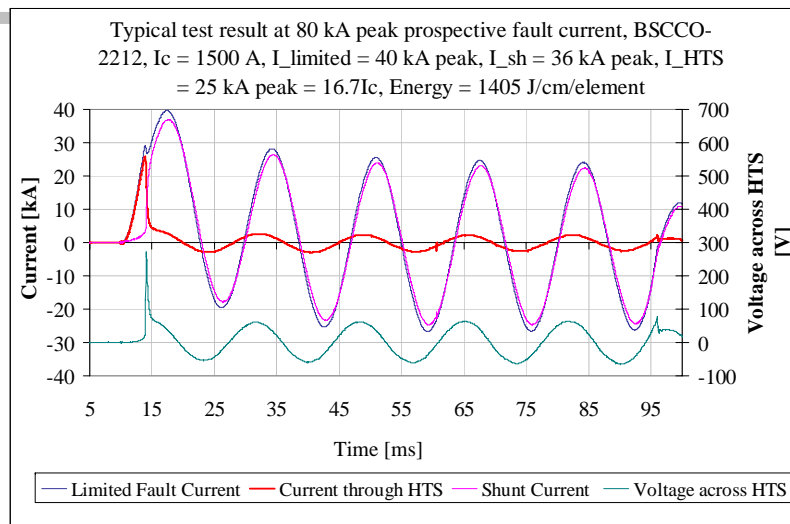


- High N value means  $I_{quench} = 2 - 3 I_c$
- High cooling surface area means shorter recovery time,  $\sim 4 - 6$  seconds
- Tested 2G elements are 40 cm long, this will be extended to  $\sim 1$  m
- Flexibility to optimize

# Melt Cast BSCCO vs. 2G Summary

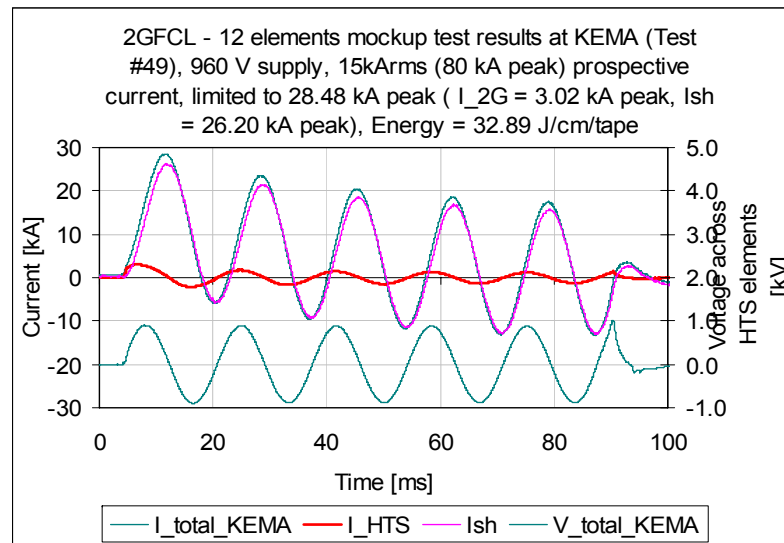
## Melt Cast BSCCO - 2212

- Ceramic with no substrate is more fragile
- Low n-value (8-12) – quench current is much higher than the critical current,  $> 10 \times I_c$
- Producing elements longer than 20 cm is a big challenge
- Using short elements increases number of parts – reduced reliability, increased complexity & cost
- Bulk material with limited cooling surface area
- BSCCO tubes, length = 20 cm, Cross-sectional area =  $1.20 \text{ cm}^2$ , Volume =  $24 \text{ cm}^3$



## 2G Tape - YBCO

- HTS is a small fraction of the tape – mostly metallic substrates & stabilizers increase mechanical strength
- High n-value (20-40) – quench current is around  $2 - 3 \times I_c$ , limiting fault current faster
- Overall mass of 2G  $<$  BSCCO for same current
- Manufacturing longer elements or continuous conductors is less challenging – significant reduction in connection losses
- Larger cooling surface area – faster recovery
- 2G tape, length = 40 cm, Cross-sectional area  $\approx 0.012 \text{ cm}^2$ , Volume  $\approx 0.48 \text{ cm}^3$



## Optimization of 2G for The SFCL

- **2G by its very nature is adaptable to the SFCL application**
  - Reduced metal content – substrate and stabilizer thickness
  - Addition of a thermal heat sink
  - Increased surface area – reduced conductor width or patterning
  - Increased Ic conductor – thick film multilayers
- **SuperPower has received an award to perform this optimization under DOE's GridWorks program**
- **GridWorks and SPI are complementary programs and fully integrated**
  - GridWorks develops optimized 2G matrix elements and elements for the SFCL
  - SPI designs, builds and tests 2G 1 $\phi$  Alpha and 3 $\phi$  Beta prototypes and installs and tests the beta prototype on the AEP grid



## SFCL FY 07 Milestones\*

1.0A	Complete AEP grid SFCL specifications	November 2006
1.0B	Identify representative U.S. utilities for study	November 2006
2.0A	Select 2G configuration for alpha prototype	December 2006
3.0A	Complete optimized 2G element configuration for alpha prototype	February 2007
4.0A	Complete optimized 2G matrix configuration for alpha prototype	April 2007
5.0A	Complete alpha prototype conceptual design	May 2007
7.1A	Complete alpha prototype cryogenic system development	June 2007
7.1B	Complete alpha prototype HV bushing and cryostat electrical insulation system development	June 2007
7.1C	Complete alpha prototype HV matrix insulation development	June 2007
7.1D	Complete overall integrated alpha prototype design review	June 2007

\* Schedule subject to revision pending further review by SuperPower, SEI, BOC, AEP and DOE

## SFCL FY 07 Milestones (cont'd.) \*

7.2A	Complete alpha prototype HV matrix design	August 2007
7.2B	Complete alpha prototype bushing and cryostat electrical insulation system design	August 2007
7.2C	Complete alpha prototype cryogenic system design	August 2007
7.2D	Stage Gate Review – Alpha prototype design review	August 2007

\* Schedule subject to revision pending further review by SuperPower, SEI, BOC, AEP and DOE

# SFCL Project Roles

Partner	Project Role
SuperPower	<ul style="list-style-type: none"> <li>• Overall project management</li> <li>• Systems integration</li> <li>• SFCL matrix design and development</li> <li>• 2G material and matrix component supply</li> <li>• Alpha and beta prototype design, fabrication and test</li> </ul>
SEI	<ul style="list-style-type: none"> <li>• Bushing and cryostat electrical insulation system design, development and manufacturing</li> <li>• Participate in prototype designs</li> </ul>
AEP	<ul style="list-style-type: none"> <li>• AEP and U.S. utility grid generalized SFCL specifications</li> <li>• Select beta prototype site and define specifications</li> <li>• Support beta prototype system studies and specification development</li> <li>• Substation design and engineering, procure and install beta prototype support equipment</li> <li>• Support beta prototype installation, commissioning, testing, data collection and analysis</li> </ul>

## SFCL Project Roles (cont'd.)

Partner	Project Role
BOC	<ul style="list-style-type: none"> <li>• Cryogenic system design and development</li> <li>• Cryogenic system instrumentation and overall system monitoring</li> <li>• LN<sub>2</sub> supply</li> <li>• Support prototype assembly and testing</li> </ul>
ORNL	<ul style="list-style-type: none"> <li>• Specialized design and testing support for high voltage matrix components in a cryogenic environment</li> <li>• Cryogenic consulting</li> </ul>
LANL	<ul style="list-style-type: none"> <li>• Investigate methods to incorporate a heat sink and improve surface area of 2G conductor</li> <li>• Assist SuperPower by testing 2G elements</li> <li>• Support matrix testing and conceptual designs</li> </ul>

## Conclusion

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**SuperPower and its team are poised to restart the SFCL program at full pace with added expertise in high voltage (SEI) and cryogenics (BOC) using superior 2G material**